Coastal Engineering Technical Note

COHESIVE ENVIRONMENT SITE CHARACTERIZATION AND MONITORING

by Andrew Morang

PURPOSE

This Coastal Engineering Technical Note (CETN) summarizes methods that can be used to characterize and monitor geological conditions at coastal projects situated in cohesive environments. These are shores where cohesive substrates (glacial till, lacustrine deposits) or erodible rock are the dominant materials that control the coast's erosional response to waves, storms, and water level changes. Cohesive processes are particularly important in the Great Lakes but also at many reservoirs and along ocean coasts where sand supply is limited and a harder stratum underlies the surficial sediment. This note also applies to portions of the gulf coast where lagoonal sediments are exposed, such as Sargeant Beach, Texas. This note does not address the unique engineering conditions caused by the extremely soft, underconsolidated clays and silts of the Mississippi Delta.

UNIQUE CHARACTERISTICS OF COHESIVE COASTS

A shore is defined as cohesive when a cohesive substratum (such as glacial till, glaciolacustrine deposits, or soft rock) occupies the dominant role in the change of the shoreline shape. Beneath any cohesionless lag deposits (sand, gravel), there is an erodible surface which plays the most important role in determining how these shorelines erode. These shores erode and recede because of the permanent removal and loss of the cohesive sediment (both from the bluff and lake bed). The sand cover may come and go, but erosion of the cohesive substratum is irreversible (Parson, Morang, and Nairn 1996). Shoreline recession does not continue without the ongoing downcutting of the nearshore sea or lake bed, and the long-term rate at which a bluff or shoreline recedes on a cohesive coast must be governed by the rate at which the nearshore profile is eroded or downcut.

Therefore, it is important to monitor the condition of the underlying cohesive material at locations where sediment supply is limited and where a project such as a jettied harbor mouth might be interrupting natural littoral transport. Questions that must be answered during a site characterization or monitoring effort include: How deep is the cohesive substratum? Does it outcrop on the surface in the project area or in the region influenced by the project? Is the cohesive substratum being downcut or is it stable? Of what is it composed, and what are its characteristics? How is the project influencing the rate of downcutting by interrupting or impounding cohesionless sediment?

To answer these questions, three types of surveys should be undertaken:

1. Bathymetric and topographic methods - used to measure the extent of cohesive exposures and the nearby seafloor with enough precision to determine if downcutting is ongoing.
2. General geologic conditions and subbottom conditions at the site - examined using geophysical methods.
3. Samples of till or other bottom sediment - collected for grain-size analyses and geotechnical testing.

SURFACE MONITORING - MORPHOLOGY, TOPOGRAPHY, AND FEATURES

Bathymetric surveys. The depth and shape of the seafloor or lake floor (and the changes over time) are among the most important data types required at all coastal sites. Hydrographic (or bathymetric) data are often collected with acoustic echo sounders from small survey boats. Most coastal U.S. Army Corps of Engineers (USACE) Districts are equipped to collect bathymetric data, and many contractors can provide these services. The fundamental problem is that acoustic surveys may not be accurate enough to measure till downcutting unless the surveys can be conducted over many years or decades. Even with the best efforts at equipment calibration and data processing, the maximum practicable achievable accuracy for coastal surveys using echo sounders is about ± 0.15 m (0.5 ft) (USACE 1994; p. 9-29). Theory, standards, and quality control for USACE hydrographic surveys are detailed in Engineer Manual (EM) 1110-2-1003 (USACE 1994) and summarized in Morang, Larson, and Gorman (1997).

Another problem with coastal hydrographic surveys is matching the data collected offshore with topographic data collected by surveyors on land. Often, boats cannot survey closer to shore than about the 2- to 3-m water depth, while surveyors cannot wade out into water deep enough to overlap the offshore coverage. Overlap is needed to ensure that both the land-based and the offshore data are properly corrected for the same vertical datum.

Sled surveys. Sleds are a means of measuring water depths less than about 6 m, including the surf zone (see CETN II-31 (Nov 93) for further information). Advantages: Sleds provide direct water depth measurements. Prisms on the sled's mast are directly measured by a total station survey system set up on land at a known benchmark. Measurement accuracy can be much better than with acoustic surveys and vertical datum or water level corrections are eliminated. Disadvantages: Surveys may not be possible in complicated topography, when the sled's runners can be snagged on rocks or other obstructions. Sleds also may not give accurate representations of the sharp topographic breaks that are sometimes found on eroded cohesive bottoms. The equipment has to be deployed at a shore that is accessible by truck. Therefore, it is not possible to use sleds at many Great Lakes sites with bluffs.

Along straight sandy shores, on-offshore sled lines spaced 300 m apart are normally adequate to characterize the bottom. However, in more complicated terrain (and cohesive shores, by their very nature are "complicated"), more closely spaced surveys may be needed.

SHOALS (Scanning Hydrographic Operational Airborne Lidar Survey). A LIDAR system, known as SHOALS, is now being used by the Corps of Engineers to survey coastal areas and inlets. The system is based on the transmission and reflection of a pulsed coherent laser light from a helicopter equipped with the SHOALS instrument pod and with data processing and navigation equipment (Lillycrop and Banic 1992; Estep, Lillycrop, and Parson 1994). In operation, the SHOALS laser pulses 200 times per second and scans an arc across the helicopter's flight path, producing a survey swath equal to about half of the aircraft altitude. A strongly reflected light return is recorded from the water surface, followed closely by a weaker return from the seafloor. The difference in time of the returns corresponds to water depth. SHOALS may revolutionize hydrographic surveying in shallow water for several reasons. The most important advantage is that the system can survey up to 8 km^2 per hour, thereby densely covering large stretches of the coast in a few days. This enables almost instantaneous data collection along shores subject to rapid changes. The system can be mobilized quickly, allowing broad-area post-storm surveys or surveys of unexpected situations such as breaches across barriers. In 1995, SHOALS surveyed the lake bed off St. Joseph, MI, revealing the complicated topography (Figure 1). Recent SHOALS improvements allow it to survey directly from water through the surf zone and across the beach; this allows efficient coverage of shoals, channels, and breaches that normally would be impossible or very difficult to survey using traditional methods, especially in winter. The prime limitation of SHOALS is that it is highly dependent on water clarity. Maximum measurement depth is over 40 m in clear tropical water, but some coastal areas at certain times of the year are unsuitable for airborne LIDAR surveys. SHOALS meets USACE Class 1 survey standards and can therefore fully substitute for acoustic methods, even for contract payment surveys.

Summary. For measurement of shallow bathymetry, airborne SHOALS surveys (USACE Class 1) are preferred because of the extensive data coverage along- and offshore and the extensive area that can be covered in a short time. However, if SHOALS cannot be used due to turbid water, sled surveys or high-quality acoustic methods must be used.

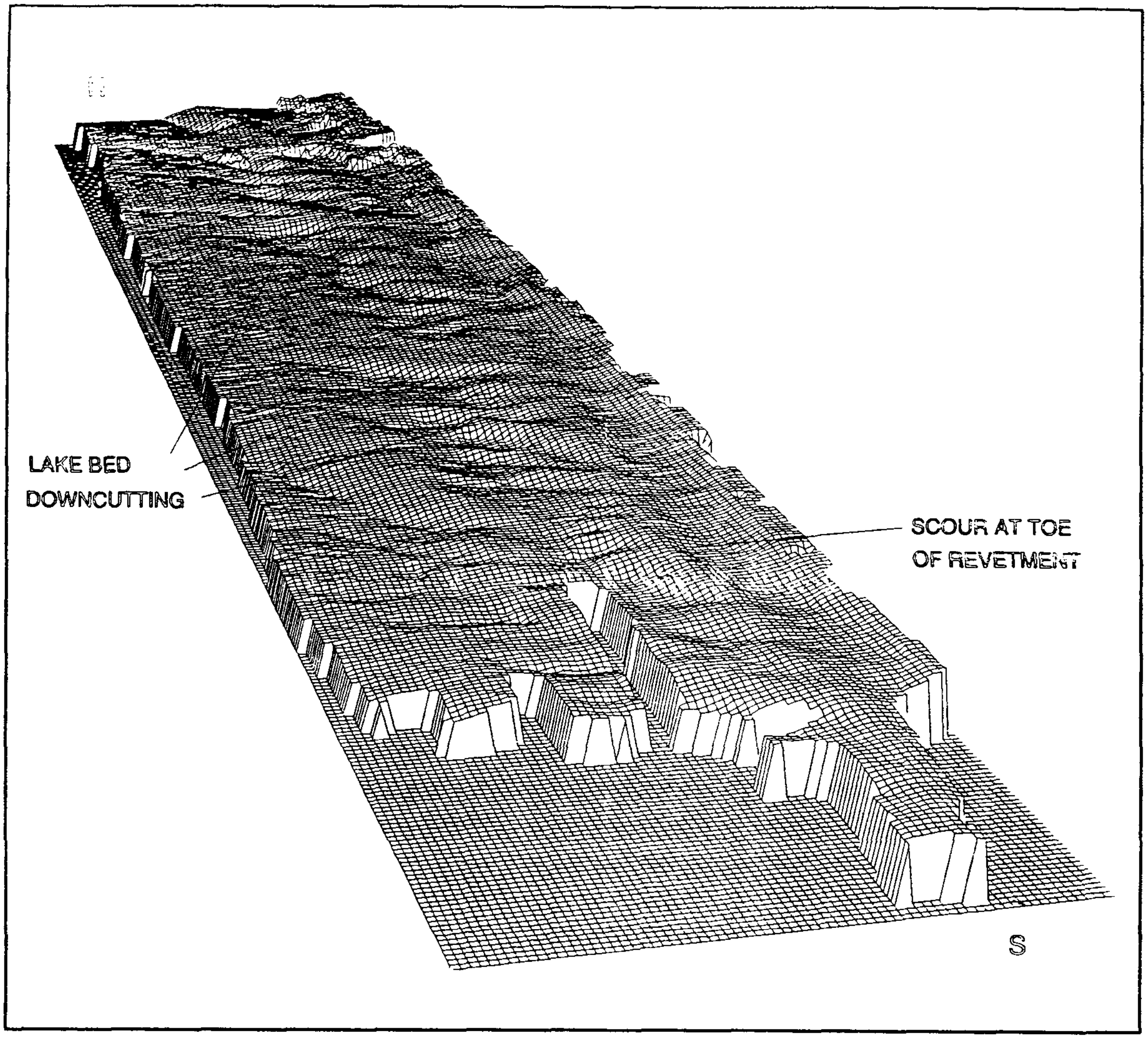

Figure 1. Three-dimensional view of complex lake bed off St. Joseph, MI, based on August, 1995, SHOALS survey. North is to upper left.

Underwater Video. The seafloor can be inspected with underwater video or still cameras deployed on remote-operated vehicles (ROV) (Figure 2). Cameras can be carried by divers, but diver inspection is costly and difficult in hazardous conditions and cold water. Unfortunately, the water at many coastal sites is so turbid that underwater visual imaging is not practical. ROV's can be rented from contractors and universities.

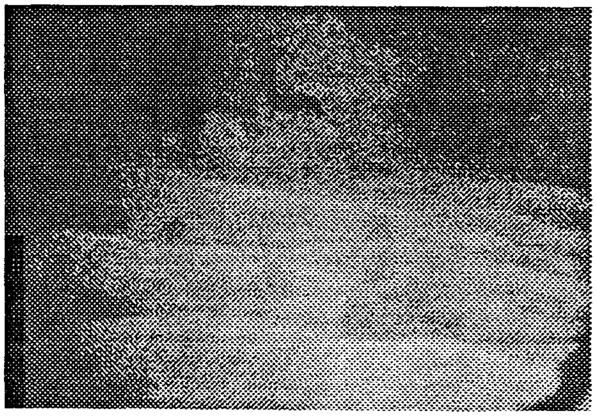

Figure 2. Lake bed off St. Joseph, MI, showing sand ripples and an outcrop of glacial clay. Very murky water - visibility 0.5 m or less. Taken with 35-mm camera on ROV; scale uncertain.

Side-scan sonar. Side-scan sonar (SSS) is a system of imaging underwater objects using high-frequency acoustic signals. Modern SSS systems have become invaluable tools to evaluate the condition of breakwaters, bridge piers, and other underwater structures (Chrzastowski and Schlee 1988; Clausner and Pope 1988; Morang 1987).

The basic side-scan system consists of three parts:

a. The transducers, mounted in a hydrodynamically streamlined body (towfish), towed at a depth below the turbulence of the survey vessel's propeller wash.
b. A graphic chart recorder combined with a signal transmitter and processor.
c. A tow cable connecting the two units (Figure 3).

Most modern SSS systems are digital and display the sonograms on a video display. They record the signals on magnetic tape or CD-ROM, although many technicians also record on chart paper while the survey is under way as a safety backup. At a later date, the recorded digital signals can be reprocessed to enhance features or examine certain portions of the seafloor at different magnifications. Also, digital systems incorporate navigation data while the surveys are under way.

Deployed a certain distance above the seafloor, the towfish emits a pulse of acoustic energy. This narrow pulse is transmitted at right angles to the tow direction and reflects from objects on the sea floor. Transducers in the towfish detect the reflections, convert them to electrical energy, and send them to the signal processing unit onboard the survey boat. Even when the signals are recorded on magnetic tape, they are typically also recorded in analog form on paper strip charts as the survey progresses. Each returning signal is plotted on the paper a distance from the center line corresponding to the time it was received. The center line on the paper represents the towfish's track line. Seafloor objects which are close to the track line are displayed near the center line, while objects located near the limit of the selected horizontal range are printed at the edges of the record. Objects directly underneath the towfish are normally not imaged because of the geometry of the sonar's beam pattern.

REMOTE (GEOPHYSICAL) SUBSURFACE MONITORING - STRATIGRAPHY AND SEDIMENT TYPE

High-resolution subbottom acoustic profiling. "High-resolution" geophysics refers to the use of acoustic sources, sound receivers, signal processing equipment, and graphic displays to define water depth and provide cross-sectional views of the sediments and strata in the uppermost ≈50 m of the sediment column (Sieck and Self 1977). *Signal* denotes any event on a seismic record from which information can be obtained (Sheriff and Geldart 1982). Everything else in the record is *noise*. The principles of subbottom seismic profiling are fundamentally the same as those of acoustic depth-sounding, but subbottom acoustic transmitters and receivers employ lower frequency, higher power signals to penetrate the seafloor (Figure 3).

Transmission of acoustic waves through sediment and rock depends upon earth material properties such as density, composition, and water and gas content (Sheriff 1980). When a wave encounters an abrupt change in elastic properties, part of the energy is *reflected* while the balance is *refracted* into the other medium. The strength of a reflected signal, and hence the ability to detect an interface, depends upon the partitioning of energy as the signal is partly reflected and partly refracted at the material interface. Mathematical relationships known as Zoeppritz' equations (detailed in Sheriff and Geldart (1982)) describe this partitioning. As the difference in impedance between the two materials increases, the *reflection coefficient* increases, thus resulting in more reflected energy. For example, a hard seafloor produces a stronger return than a soft seafloor. For most interfaces within the earth, impedance contrasts are small and typically less than 1 percent of the energy is reflected. This is why sophisticated data processing and noise-reduction procedures are needed to reveal strata deep within the earth. Because the seafloor, the sea surface, and the base of the weathering layer are relatively strong reflectors, they are responsible for most of the multiple reflectors that often obscure portions of subbottom returns.

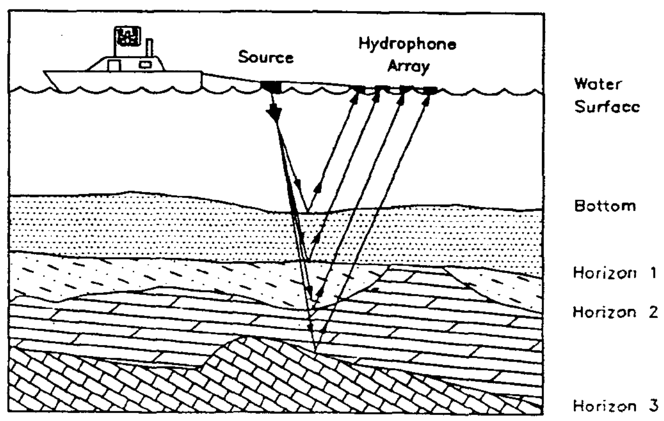

Figure 3. Subbottom profiling from small survey boat.

Most mathematical treatments of acoustic energy partitioning in the earth assume a planar surface and, therefore, specular reflections. If the surface is irregular and has bumps of height *d*, reflected waves from the bumps reach the receiver before the waves from the rest of the surface by a distance 2*d*. These can be neglected where $2d/\lambda < \frac{1}{4}$ (the "Rayleigh criterion"), *i.e.*, when $d < \lambda/8$ (Sheriff and Geldart 1982). This tells us that there is a practical limit to the size of features that can be detected on a surface which depends on the frequency (and hence the wavelength), of the acoustic signal source. For example, if a Bubble Pulser source is used with a dominant frequency of 400 Hz (Table 1), the wavelength λ in sandstone, assuming a velocity of 2,000 m/s, is equal to 5 m. Therefore, an irregularity *d* would not be detected if it were less than about $\frac{1}{8} \times 5$ or 0.6 m high. In summary, interpretors of seismic records should beware that a surface, such as a till layer, that appears uniform on an acoustic record may actually be quite irregular. Further details on signal penetration and transmission of acoustic signals are summarized in Morang, Larson, and Gorman (1997).

Lack of signal penetration is caused by many conditions. Coarse sand and gravel, glacial till, and highly organic sediments are often difficult to penetrate with conventional subbottom profilers, resulting in records with data gaps. The lack of penetration itself is a diagnostic tool. For example, gassy sediments cause serious signal degradation and gaps in records. Often, little useful subbottom data can be collected in estuaries and river mouths because they contain so much organic material. For example, much of Chesapeake Bay is almost opaque to high-resolution seismic imaging. In these conditions, cores may be necessary to fill in the missing geological information. Digital signal processing of multi-channel data can sometimes extract useful data despite poor signal penetration or noise. However, signal processing is not magic and there are limits to what it can achieve in difficult environments.

The two most important parameters of a subbottom seismic reflection system are its vertical resolution and penetration. As the dominant frequency of the output signal increases, the resolution, or the ability to differentiate closely spaced reflectors, becomes more refined. Unfortunately, raising the frequency of the acoustic pulses increases attenuation of the signal and consequently decreases the effective sediment penetration. Thus, it is a common practice to use two seismic reflection systems simultaneously during a survey; one of high-resolution capabilities and the other capable of greater penetration.

The thinnest bed or layer that can be detected is about $\lambda/4$ (Sheriff 1977). Using the example of a 400-Hz signal in sandstone with $\lambda = 5$ m, layers as thin as 1.25 m should be detectable (providing, of course, that there are sufficient acoustic impedances to produce measurable reflections). If a 3.5-kHz profiler is used, the wavelength in sandstone is much smaller, about 0.6 m, and layers about 0.15 m thick can be detected.

Ground-penetrating radar (GPR). Commercially available short-pulse radar equipment used for subbottom imaging consists of a control unit, magnetic tape recorder, power supply, and a combination transmit and receiving antenna unit. Electromagnetic energy is reflected from earth materials because of variations in dielectric contrast and electrical resistivity. Because the contrasts differ and may exceed the acoustic anomalies produced by the same materials, GPR can sometimes reveal strata and material changes that might not be revealed by acoustic methods (Sellmann, Delaney, and Arcone 1992). Usually, GPR can only be used in freshwater environments. In most oceanic coastal areas, subsurface units such as fine-grained estuarine and lagoonal clays and coarse-grained sand units contain salt water that causes severe signal attenuation. However, GPR can be successful when imaging wide and high barriers where there is a thick lens of fresh water.

Using both acoustic profiling equipment and ground-penetrating radar in freshwater surveys permits researchers to obtain more complete subbottom data because the two approaches respond to different physical properties and have different spatial sensitivities. The resolution of GPR is typically less than that of high-resolution acoustic profilers. However, despite the lower resolution, GPR is valuable because it can sometimes image areas that are opaque to acoustic energy (*e.g.*, gas-charged sediments) or do not possess impedance contrasts adequate to produce acoustic signal returns. Data from GPR can be processed so that they resemble an acoustic subbottom profiling record (Figure 4).

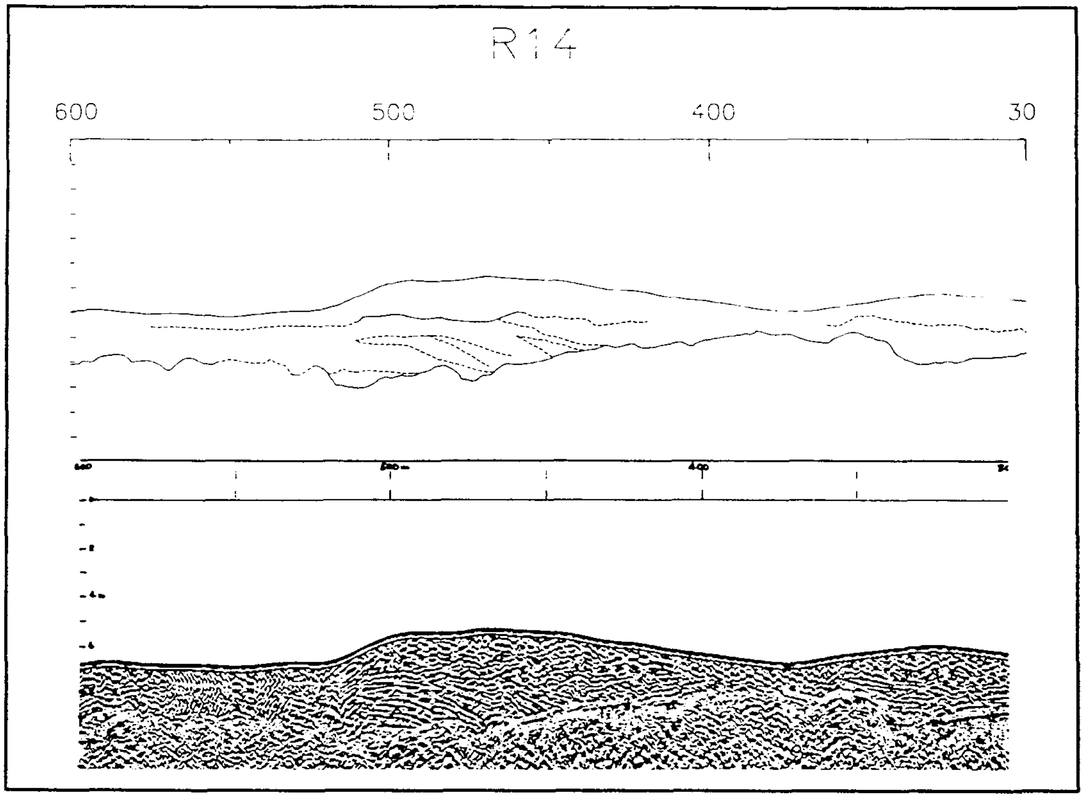

Figure 4. Example of GPR data and interpretation from St. Joseph, MI. Upper units contain sands or silts. There is effectively no signal penetration through clay, and everything below the top of the clay reflector is random noise. GPR system was mounted on a plastic sled that was towed along the lake bed.

Direct Subsurface Monitoring

Grab sampling and coring. Actual samples of the beach and offshore sediment are needed for a number of reasons: matching fill to native beach material; evaluating engineering properties of offshore soils for foundation design; measuring till downcutting in laboratory flume experiments; determining stratigraphy to aid interpretations of geophysical surveys. There are a variety of grab type samplers of different sizes and design that are used for collecting uncohesive and soft cohesive surface sediments (Bouma 1969). Most consist of a set of opposing, articulated scoop-shaped jaws that are lowered to the bottom in an open position and are then closed by various trip mechanisms to retrieve a sample. Many grab samplers are small enough to be deployed and retrieved by hand while others require some type of lifting gear. If there is gravel in the sample, many liters of sample may be needed for reliable grain size distribution testing (see Chapter 5 of EM 1110-2-1810 (USACE 1995)). Standard sampling equipment and techniques used by the Corps of Engineers are described in EM 1110-1-1906 (USACE 1996b), and geotechnical laboratory procedures are detailed in EM 1110-2-1906 (USACE 1996a).

With the hard till frequently encountered in the Great Lakes, standard grab samplers may be unable to recover samples. Under these circumstances, heavy lifting equipment is needed. At St. Joseph, large blocks of lake bed were recovered with a 2.3-m^3 clam bucket that was lifted by a derrick on a barge (Figure 5). After hoisting to the deck of the barge, the till samples were washed and then trimmed with a machete into a block about 0.3 m on a side. They were then wrapped with plastic and placed in wooden boxes slightly larger than the dimensions of the blocks (Figure 6). To preserve moisture, Hydrostone, a gypsum cement similar to plaster of Paris, was poured around each sample, filling the void between the block and the wood sides of the box. The boxes were shipped to Ohio River Division's laboratory for x-ray diffraction analysis and other tests. Pieces of the samples were tested in a flume to determine erosion rates in water containing different concentrations of sand (Parson, Morang, and Nairn 1996; Figure 7). These types of tests require large undisturbed samples. Obtaining such samples is expensive and time-consuming, but the resulting data are unavailable from insitu methods. Costs can be reduced if construction equipment is already in the area.

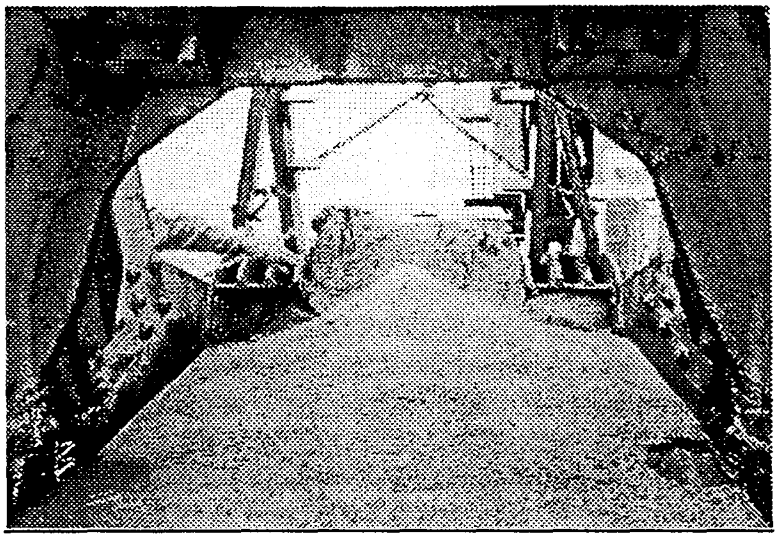

Figure 5. 2.3-m^3 clam bucket used at St. Joseph, MI, to collect sediment from the lake bed, July 1993. View of interior of bucket showing hand for scale. Sand covers the till and has to be washed off.

Figure 6. Block of cohesive till 0.03 m^3 is wrapped in plastic to preserve moisture content. Block was then encased in gypsum cement.

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Table 1
Summary of Survey Systems

Seafloor and Water Column		
Acoustic	Frequency (kHz)	Purpose
Echo sounder (single beam)	12 - 200	Measure water depth for bathymetric mapping
Echo sounder (multi-beam)	75 - 455	Map seafloor topography and structures
Water column bubble detector (tuned transducer)	3 - 12	Detect bubble clusters, fish, flora, debris in water column
Side-scan sonar	38 - 455	Map seafloor topography, sediment type, texture, outcrops, man-made debris, structures, pipelines
Electromagnetic (laser)		
SHOALS helicopter LIDAR		Measure water depth for bathymetric mapping, USACE Class A (± 15 cm)
Direct (manual) method		
Sled surveys	(Not applicable)	Measure water depth for bathymetric mapping, usually across channels or perpendicular to beaches
Subbottom Profilers		
Tuned transducers	3.5 - 7.0	High-resolution subbottom penetration
Electromechanical:		
Acoustipulse®	0.8 - 5.0	Bottom penetration to ~30 m
Uniboom®	0.4 - 14	15- to 30-cm resolution with 30- to 60-m penetration
Bubble Pulser	~ 0.4	Similar to Uniboom®
Sparker:		
Standard	50 - 5,000 Hz	Use in salt water (minimum 20 ‰), penetration to 1,000 m
Optically stacked	(Same)	Improved horizontal resolution
Fast-firing 4 KJ & 10 KJ	(Same)	Improved horizontal and vertical resolution
De-bubbled, de-reverberated	(Same)	Superior resolution, gas-charged sediment detection
Multichannel digital	(Same)	Computer processing to improve resolution, reduce noise

(From Sieck and Self (1977), EG&G®, Datasonics®, Reson®, and other company literature)

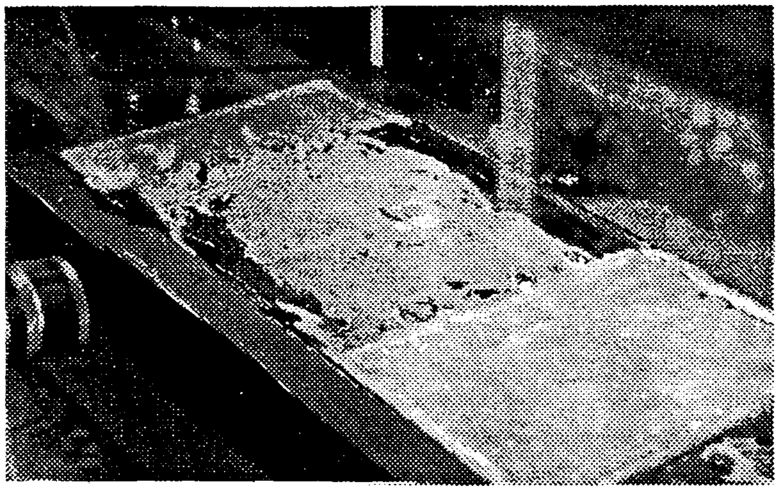

Figure 7. Flume test of St. Joseph till conducted at the Hydraulics Laboratory of the National Research Council of Canada in Ottawa, August 1994. Block has eroded around the edges after 3-hr. 40-min. test with clear water.

References:

Bouma, A. H. (1969). *Methods for the study of sedimentary structures.* John Wiley and Sons, New York.

Chrzastowski, M. J., and Schlee, J. S. (1988). "Preliminary sidescan-sonar investigation of shore-defense structures along Chicago's northside lake front: Wilson Avenue groin to Ohio Street beach," *Environmental Geology Notes* 128, Department of Energy and Natural Resources, Illinois State Geological Survey, Champaign, IL.

Clausner, J. E., and Pope, J. (1988). "Side-scan sonar applications for evaluating coastal structures," Technical Report CERC-88-16, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Estep, L. L., Lillycrop, W. J., and Parson, L. E. (1994). "Estimation of maximum depth of penetration of a bathymetric lidar system using a Secchi disk database," *Marine Technology Society Journal,* 28, 31-36.

Lillycrop, W. J., and Banic, J. R. (1992). "Advancements in the U.S. Army Corps of Engineers hydrographic survey capabilities: the SHOALS system," *Marine Geodesy,* 15, 177-185.

Morang, A. (1987). "Side-scan sonar investigation of breakwaters at Calumet and Burns Harbors on southern Lake Michigan." Miscellaneous Paper CERC-87-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Morang, A., Larson, R., and Gorman, L. T. (1997). "Monitoring the coastal environment; Part III: Geophysical and research methods," in press, *Journal of Coastal Research,* Vol 13.

Parson, L. E., Morang, A., and Nairn, R. B. (1996). "Geological effects on behavior of beach fill and shoreline stability for southeast Lake Michigan," Technical Report CERC-96-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sellmann, P. V., Delaney, A. J., and Arcone, S. A. (1992). "Subbottom surveying in lakes with ground-penetrating radar," CRREL Report 92-8, U.S. Army Engineer Cold Regions Research & Engineering Laboratory, Hanover, NH.

Sheriff, R. E. (1977). "Limitations on resolution of seismic reflections and geologic detail derivable from them." *Seismic stratigraphy - Applications to hydrocarbon exploration.* C. E. Peyton, ed., Memoir 26, American Association of Petroleum Geologists, Tulsa, OK, 3-14.

Sheriff, R. E. (1980). *Seismic stratigraphy.* International Human Resources Development Corporation, Boston, MA.

Sheriff, R. E., and Geldart, L. P. (1982). *Exploration seismology, Volume 1: History, theory, and data acquisition.* Cambridge University Press, Cambridge, UK.

Sieck, H. C., and Self, G. W. (1977). "Analysis of high resolution seismic data." *Seismic Stratigraphy - Applications to hydrocarbon exploration*. C. E. Peyton, ed., Memoir 26, American Association of Petroleum Geologists, Tulsa, OK, 353-385.

U.S. Army Corps of Engineers. (1994). *Hydrographic surveying*. Engineer Manual 1110-2-1003, Washington, D.C.

U.S. Army Corps of Engineers. (1995). *Coastal geology*. Engineer Manual 1110-2-1810, Washington, D.C.

U.S. Army Corps of Engineers. (1996a). *Laboratory soils testing*. Engineer Manual 1110-2-1906, Washington, D.C.

U.S. Army Corps of Engineers. (1996b). *Soil sampling*. Engineer Manual 1110-1-1906, Washington, D.C.